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In an earlier note Cimbala and Park (1990) presented a method for calibrating constant temperature hot wires in incompressible gas flow which accounts for ambient temperature changes. Their method involves the retention of the temperature dependence in a form of King's Law. However, in practice the method proves difficult to implement due to a numerical difficulty in finding a best fit to the assumed functional form. This note presents a modified version of the method of Cimbala and Park which does not seen to have the numerical difficulty, as well as some further comments on the method.

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Kim, J.; Moin, P.; Moser, R. D. 1987: Turbulence statistics in fully-developed channel flow at low Reynolds number. J. Fluid Mech. 177, 133–166
Kreid, D. K. 1974: Laser doppler velocimeter measurements in nonuniform flow: error estimates. Appl. Optics 13, 1872–1881
McLaughlin, D. K.; Tiederman, W. G. 1973: Biasing correction for individual realisation of laser anemometer measurements in turbulent flows. Phys. Fluids 16, 2082–2088
Mazumder, M. K.; Wauchio, S.; McLeod, P. C.; Ballard, G. S.; Mozumdar, S.; Caraballo, N. 1981: Skin friction drag measurements by LDV. Appl. Optics 20, 2832–2837
Neiderschulte, M. A.; Adrian, R. J.; Hanratty, T. J. 1990: Measurements of turbulent flow in a channel at low Reynolds numbers. Expts. Fluids 9, 222–230
Reischman, M. M.; Tiederman, W. G. 1975: Laser-doppler anemometer measurements in drag-reducing channel flows. J. Fluid Mech. 70, 369–392
Spalart, P. R. 1988: Direct simulation of a turbulent boundary layer up to $R_\theta = 1410$. J. Fluid Mech. 187, 61–98
Van Driest, E. R. 1956: On turbulent flow near a wall. J. Aeron. Sci. 23, 1007–1012
Zhou, Y.; Antonia, R. A. 1992: Convection velocity measurements in cylinder wake. Expts. Fluids 13, 63–70

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A note on the temperature-dependent hot-wire calibration method of Cimbala and Park

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Abstract. In an earlier note Cimbala and Park (1990) presented a method for calibrating constant temperature hot wires in incompressible gas flow which accounts for ambient temperature changes. Their method involves the retention of the temperature dependence in a form of King's Law. However, in practice the method proves difficult to implement due to a numerical difficulty in finding a best fit to the assumed functional form. This note presents a modified version of the method of Cimbala and Park which does not seem to have the numerical difficulty, as well as some further comments on the method.

1 Introduction

In an earlier note, Cimbala and Park (1990) presented a version of King's law which retains a dependence on the ambient temperature, and they showed that this method allows reasonably accurate computation of the velocity as a function of hot-wire voltage over a wide range of temperatures. In common with most practical use of King's law, the calibration coefficients computed using their method are dimensional, and this ties into a numerical difficulty with the method, which is that finding the values of the calibration coefficients which give the best fit to the assumed form of the calibration curve is numerically unstable, and requires substantial effort in order to obtain convergence. By using a nondimensional form of King's law, the calculation of the best fit is simplified by the fact that the nondimensional coefficients and variables are all of order 1.

The starting point is the following form of King's Law:

$$Nu = a + b\,Re^n \tag{1}$$

where Nu is the Nusselt number and Re is the Reynolds number based on wire diameter and the local flow velocity U normal to the wire. Following Blackwelder (1981) and modeling the hot wire as a circular cylinder, the Nusselt number is defined by

$$Nu = \frac{q}{\pi\, l_w\, k\,(T_w - T_a)}$$

where q is convective heat loss, l_w is the hot-wire length, $k = k(T)$ is the thermal conductivity and T_w and T_a are the wire operating temperature and the ambient temperature, respectively. Assuming that the heat loss is equal to the power dissipated in the wire,

$$q = \frac{e_w^2}{R_w}$$

where e_w is the voltage across the hot wire and R_w is the (nominally fixed) hot-wire resistance. This gives

$$Nu = \frac{e_w^2}{\pi\, R_w\, l_w\, k\,(T_w - T_a)} \tag{2}$$

As in Cimbala and Park, k and the kinematic viscosity ν are evaluated at $T = \frac{1}{2}(T_w + T_a)$ (Sutherland's law) and at the ambient pressure. Substituting Eq. 2 into Eq. 1 provides the desired explicit dependence on the ambient temperature.

Cimbala and Park rewrite this equation in dimensional form with 5 calibration parameters, corresponding to a hot-wire offset voltage, the wire temperature T_w, the exponent n, and dimensional forms of the coefficients a and b. The offset voltage is not a calibration parameter in the same sense as the other parameters as it can be independently measured

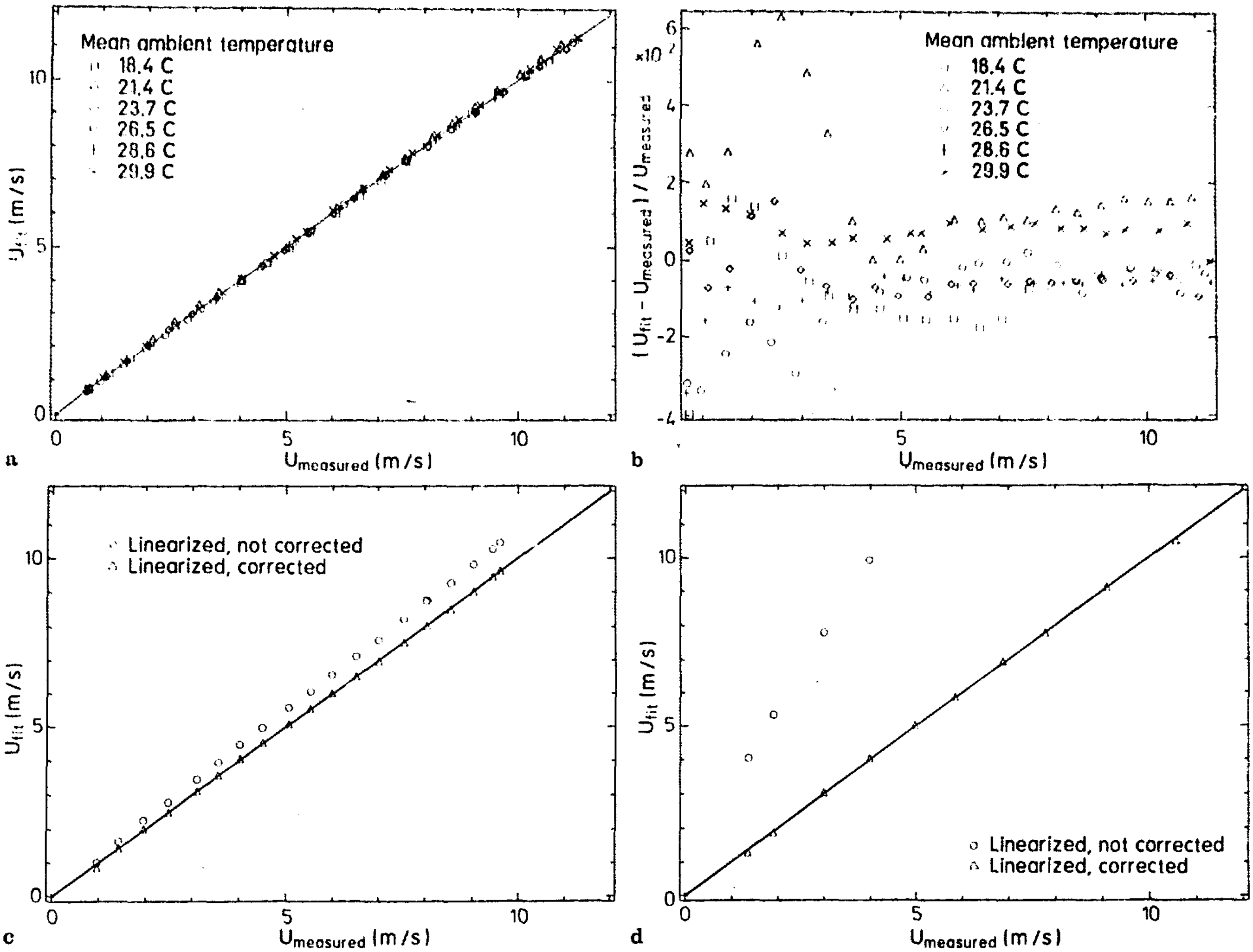

Fig. 1. a Hot-wire calibration data used for finding the coefficients in Eq. (1), linearized using the resulting coefficients. The data cover an ambient temperature range of 18–30 °C. The solid line has slope 1; **b** deviation of the fit velocities (computed using Eq. (1) and the coefficients in Table 1 from the measured velocities, $(U_{fit} - U_{measured})/U_{measured}$; **c** hot-wire calibration data using the same hot-wire as for the data in Fig. 1a, measured on a different day, linearized using the coefficients from Table 1 and then linearly corrected; **d** hot-wire calibration data using a different hot-wire from that used for the data in Fig. 1a, linearized using the coefficients from Table 1 and then linearly corrected

and is not a property of the hot wire itself, and therefore is not used as a parameter in the present method.[1]

If the equation is evaluated directly in the form given here, Nu and Re are of order 1 and minimization of

$$\chi^2 = \sum (Nu(U_i, T_{ai}, P_i; a, b, n, T_w) - Nu_i)^2$$

is straightforward, giving the values of the fit parameters (a, b, n, T_w) for use in calibrating the hot wire. Although T_w is a dimensional value of order 100 K, and is used as one of the fit parameters, this does not affect the minimization scheme since it is combined into Nu which is of order 1. The expression for Nu gives $e_w(U, T_a)$ and is directly invertible, so $U(e_w, T_a)$ is easily calculated once the values of the fit parameters are known.

A large quantity of data was taken in air with a commercially available tungsten hot wire at different ambient temperatures spanning a range from 18–30°C, and values of the fit parameters were determined using a simplex method (Press et al., 1988) to search for a multi-dimensional minimum of χ^2 in the (a, b, n, T_w) parameter space. The physical properties of air were computed by interpolation from the tabulation in Hilsenrath (1955). The simplex method requires input of an initial guess of several points in the coefficient space, and a tolerance defining how close to the actual minimum the result must be. In the present case, a single initial guess is provided, and the other points are produced by moving 15% of the initial value along each axis in the parameter space. The tolerance is defined as the maximum allowable (Euclidean) distance from a minimum in parame-

[1] It is straightforward to include an offset voltage by replacing the hot-wire voltage e_w with $e - e_{off}$, where e and e_{off} are the measured hot-wire signal and offset voltages respectively, and then minimizing with respect to the additional parameter e_{off}

Table 1. Best fit parameters for the hot-wire calibration data shown in Fig. 1a

Parameter	Best fit value
a	0.2318
b	0.3171
n	0.4225
T_w	381.0 K

ter space, and $1 \cdot 10^{-12}$ was found to give accurate results. The fit parameters found using the experimental data are listed in Table 1. The value of T_w in Table 1 which minimizes χ^2 should reflect the actual hot-wire temperature, which is selected to be 500 K by a setting in the hot-wire circuit, and it is unclear why the value found by the calculation is so much smaller. The method was found to be very tolerant of the choice of the initial guess, and for the example data always converged to the same values of the parameters.

Figure 1a is a plot of the data in the form of U_{fit} vs. U_{measured}, with U_{fit} evaluated using the coefficients in Table 1, and Fig. 1b is a plot showing the relative deviation of U_{fit} from U_{measured}. The average deviation of the data from the measured values was 0.06 m/s, which is similar to that found by Cimbala and Park, and it can be seen that the relative deviation increases for low velocities. Further calibration data for the same hot wire was collected on a different day from the data shown in Fig. 1a and 1b, and is shown in Fig. 1c. The result of processing the data using Eq. 1 is a straight line, which may then be corrected. After this second, linear correction is applied the relative deviations (not shown) are all less than 1% for $U > 2$ m/s, with an average deviation of 0.04 m/s. This demonstrates that Eq. 1 is a good linearizer of the data, but it cannot be used for velocity measurement without a minimal recalibration to determine the linear correction, which is probably caused by hot-wire drift from the effects of oxidation or other factors. A linear correction was also used by Cimbala and Park.

The values of the coefficients in Table 1 were also used to linearize data taken for a different hot wire of the same make and model and Fig. 1d is an example of the fit for such a hot wire. Again, after applying a linear correction, the deviations in this case are all less than 1% for $U > 2$ m/s, with an average deviation of 0.05 m/s.

From an examination of the figures, it appears that there is a small but consistent curvature in the "linearized" data sets. In an attempt to correct for this a quadratic term was added to the King's Law expression, resulting in the form:

$$Nu = a + b\,Re^n + c\,Re^{2n}$$

The additional term can be thought of as the next term in a power series for Nu (Re^n), and so is not entirely without foundation. This expression is also invertible in closed form. Using the data set of Fig. 1a, and the simplex method described above, the value of c was found to be 5 orders of magnitude less than a and b, and the deviation was not reduced.

The experiments for which this effort were undertaken have been moved to a facility where the temperature is typically constant to within 0.1 K per hour, and under these circumstances it is simpler to compute (a, b, n, T_w) using calibration data taken for each experiment, rather than attempting to use a single set of coefficients obtained from a large quantity of data.

In conclusion, the temperature dependent King's law given in Eqs. 1 and 2, combined with a linear correction, provides an effective means for making hot-wire measurements in facilities where variations in ambient temperature make the more traditional method impractical or impossible to use. The modified version given in this note is useful because of the ease with which the fit parameters may be computed and is philosophically satisfying because the coefficients appearing in the equation are dimensionless. Treating King's law as a truncated power series for Nu (Re^n) and adding the next term in the series was shown to have no significant effect on the quality of the fit to the data. Further, the values computed for one hot wire have been shown to satisfactorily linearize calibration data from a different hot wire of similar construction, so that extensive calibration measurements over a wide temperature range need be performed for only one hot wire, and the resulting calibration parameters then used for several.

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References

1. Blackwelder, R. F. 1981: Hot-wire and hot-film anemometers. Methods Exp. Physics, 18, 259–314
2. Cimbala, J. M.; Park, W. J. 1990: A direct hot-wire calibration technique to account for ambient temperature drift in incompressible flow. Exp. Fluids 8, 299–300
3. Hilsenrath, J. et al 1955: Tables of thermal properties of gases. National Bureau of Standards Circular 564, U.S. Dept of Commerce, Washington D.C.
4. Press, W. H.; Flannery, B. P.; Teukolsky, S. A.; Vetterling, W. T. 1988: Numerical recipes in C. Cambridge: University Press

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Effects of small changes in initial conditions on mixing layer three-dimensionality

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1 Introduction

Experimental studies conducted in the 1970's began to show that the development of plane mixing layers was influenced not only by the formation and interaction of large-scale spanwise vortices, but also by a secondary structure in the form of streamwise vortices (Brown and Roshko 1974). Several studies were subsequently conducted on the origin and evolution of this secondary structure, but almost all of them were limited to flow visualization data obtained mainly in the near-field region of the mixing layer (see Bell and Mehta 1992, for a review).

The first detailed quantitative investigation of these streamwise structures was conducted in a two-stream mixing layer with a velocity ratio of 0.6 and a Reynolds number of about $\sim 2.9 \times 10^4$ (Bell and Mehta 1992). Measurements of the mean streamwise vorticity indicated that small disturbances (naturally present) in the flow were initially amplified just downstream of the first spanwise roll-up, leading to the formation of streamwise vortices, in agreement with earlier observations. The streamwise vortices, with average circulation equivalent to about 10% of the initial spanwise circulation, first appeared in clusters containing vortices of both signs, but re-organized further downstream to form counter-rotating pairs. This vortex structure was found to grow in size, scaling approximately with the mixing layer vorticity thickness, and weaken, the maximum mean vorticity diffusing as approximately $1/X^{1.5}$. The data suggested that the streamwise structures persisted through to the far-field region, although they were weak enough by this point that the mixing layer may be considered to be nominally two-dimensional.

Mixing layers are known to be very sensitive to initial conditions, and so one question which naturally arose in the above study was to what extent the details of the observed three-dimensionality were facility dependent, i.e. would the nature of the three-dimensionality be the same in *all* wind tunnels? Hence, the objective of the present study was to establish the sensitivity of the three-dimensionality to small changes in initial conditions. In particular, qualitative and quantitative changes in the streamwise vorticity, and its effects on the mixing layer mean and turbulence properties, were to be determined in the near- and far-field regions through direct measurements. The slight change in initial conditions was achieved by simply swapping the high- and low-speed sides in the *same* mixing layer wind tunnel, while maintaining the same velocity ratio.

2 Experimental apparatus and techniques

The experiments were conducted in a *Mixing Layer Wind Tunnel*, consisting of two separate legs which are driven independently (Bell and Mehta 1992). In the "base" case, the leg driven by the larger blower was operated to provide a free-stream velocity of 15 m/s, whereas the other leg was run at 9 m/s. In the other case, designated as the "reversed" case, the high- and low-speed sides were interchanged. Both cases were run at the same relative velocities, thus giving a fixed velocity ratio, $\lambda = U_2/U_1 = 0.6$. The boundary layers on the splitter plate were laminar at these running conditions, with the measured properties tabulated in Table 1. For a given velocity, the boundary layer properties between the two sides of the splitter plate agree reasonably well.

Measurements were made using a cross-wire probe mounted on a 3-D traverse and linked to a fully automated data acquisition and reduction system controlled by a MicroVax II computer. Data were obtained in $Y-Z$ planes at several streamwise locations, with the probe oriented in the uv- and uw-planes. Individual statistics were averaged over 5,000 samples obtained at a rate of 400 samples per second. The data consisted of all three components of mean velocity, five independent components of the Reynolds stress

Table 1. Initial boundary layer properties

Condition	U_e (m/s)	δ_{99} (cm)	θ (cm)	Re_θ	H
High-speed side, base case	15.0	0.40	0.053	525	2.52
Low-speed side, base case	9.0	0.44	0.061	362	2.24
High-speed side, reversed case	15.0	0.39	0.054	532	2.29
Low-speed side, reversed case	9.0	0.44	0.055	322	2.61

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